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Estimation of thermal and moisture movements and stresses: Part 1

Recognition of the location and extent of movements in building materials and components is essential for the satisfactory design of joints and fixings and the prevention of cracking. This is particularly important with regard to long-term performance and the avoidance of excessive maintenance.

This digest is intended primarily as a source of data on the physical characteristics of building materials needed to assess their movements, or the stresses resulting from restrained movements, due to changes in temperature and moisture content. It also includes elementary methods for assessing the extent of these effects but does not deal with the practical consequences of movements in particular parts of buildings. It is published in three parts: Part 1 discusses movements, their sources and design strategies for accommodating them, and the causes of deformation and stress; Part 2 (published August 1979) is an analysis of thermal and moisture effects and includes tabulated data needed to assess the change of size and shape of materials; Part 3 (published September 1979) gives guidance on estimating deformations and associated forces and stresses.

Restrained and unrestrained movements

Few parts of a building are immune from potential changes of size or shape (inherent deviations); whether they occur as actual changes, resulting in overall or differential movement, or as stresses depends on the amount of restraint offered to them. In many cases both effects will be present, with partial restraint limiting the amount of actual movement and giving rise to a 'balancing' stress. The data and methods in this digest enable the magnitudes of these effects to be estimated for a range of materials. Because of the difficulty of accurately predicting restraint and the other variabilities in materials and conditions that occur in practical building situations, sophisticated methods are little better for this estimation than elementary ones. The essential needs are to recognise where inherent deviations are liable to occur and to determine the order of magnitude of their effects, so that adequate provision can be made for them in design.

Problems of relative movement, especially that due to thermal expansion and contraction, tend to be more marked in modern forms of construction because of:

(a) the use of larger units with fewer joints, which results in greater potential movement at any one joint;

(b) the greater thermal movement of some of the newer materials, especially plastics, which have coefficients of thermal expansion up to 10 times greater than most traditional materials;

(c) the use of thin sections whose low thermal capacity increases the range of temperature experienced by a material when subjected to environmental extremes.

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Failure to take adequate account of movements is the underlying cause of a high proportion of building defects and failures, at scales ranging from the complete structure to joinery and finishes. The fabric of a building should be considered as a complex of active mechanisms, not as being physically inert. The form of the building as well as the nature of the materials used will need to be considered, since some of the most significant effects are caused by two or three-dimensional interactions.

Design strategies

When the strategy of a design is to accommodate movements, as is more usual, rather than resist induced stresses, considerable care in design and construction is needed to ensure that fixings, bearings and other parts intended as load-bearing mechanisms actually function as such. In building, unlike civil engineering, there are as yet few well-proven details or techniques for dealing with this problem. The requirement to accommodate movements is also likely to apply to various kinds of non-loadbearing joint, which may need to perform this function in addition to others such as weatherproofing or sound insulation. Since many types of movement continue throughout the life of a building, it is essential that moving parts are not subsequently prevented from moving, eg through corrosion or the accumulation of dirt, as the potential of unintentionally-restrained movements for causing damage is considerable.

There are some cases when it may be possible to design for the potential movements of a component or material to be restrained. This implies that the induced stresses, together with any co-acting stresses from other sources, should not exceed the permissible stress for the material or produce unacceptable deformations in other directions. Designing for restraint tends to be practicable only over small dimensions or areas or, at the other extreme, as a facet of the behaviour of whole structures. Examples of the former are found in applied finishes, for which bond strength, together with the strength of the finishing material and the stiffness of the backing construction, determine the maximum spacing of joints. An example of the latter is a structure designed to resist potential temperature movements in exposed members. In some situations, there may be internal restraint and consequent induced stresses even in components or materials that are free to deform.

Other types of movement

While this digest covers only thermal and moisture effects, there are several other sources of movement that may need to be considered. Depending on circumstances, these may either add to the movement to be accommodated at a particular point, or make additional provision necessary elsewhere. The most widely relevant will be structural deflections, creep (especially creep-shortening of columns) and foundation movements. Restraint of structural movements will, however, reduce and not increase stress in the member concerned, although additional stress will be induced in whatever part of construction carries the redistributed load. It is always desirable for structural engineers to be asked to advise on the extent of structural movements as they affect non-structural parts of the building fabric. The data on moduli of elasticity given in this digest may prove useful in assessing structural deflections. Other, less common sources of movement include physical changes such as loss of volatiles and the formation of ice and crystalline salts, and chemical changes such as corrosion, sulphate attack and carbonation (See Digest 223).

Related aspects of design

There are a number of related or dependant factors that may need to be considered in designing for movements or induced stresses. Where movements are to be accommodated at joints or fixings, it will be necessary also to take account of inaccuracies in components and site work. With some designs of joint the same mechanism, eg a baffle with air seal or a site-applied sealant, accommodates both inaccuracies and movements. In other cases, as with many types of fixings, adequate adjustment to compensate for inaccuracies must be possible if the provision for movements is to function as intended. In all cases, both inaccuracies and movements must be assessed realistically in order to achieve a satisfactory chance of initial fit and of dependable performance in use. The principles of designing for fit are given in Digest 199, and a fuller description, together with design aids, is contained in the BRE Handbook Graphical Aids for Tolerances and Fits.

The extent of thermal effects in an exposed material is heavily dependent on its disposition and surface character; the problem of accommodating the effects will obviously be lessened if designs are chosen or adjusted with the express aim of limiting the severity of exposure. It may be possible, for example, to provide partial protection for vulnerable parts by means of local surface features such as projections or overhangs or, in some instances, incorporate full protection into a design, as in an 'upside-down' roof. Temperature extremes in any exposed construction will depend in part on how well it is insulated from the interior of the building and will be moderated as its mass and thermal capacity increase, and by the use of light-coloured surfaces. External insulation will greatly reduce the temperature range experienced by the building envelope, although its own surfacing, if thin, will be subjected to severe extremes. In designing to accommodate movements, the possible problems of fatigue and noise generation should not be overlooked. Both are more likely to be significant when materials, fixings and joints are subject to frequent movements and high rates of change.

Sources of movement

Thermal movements

Every material is subject to some increase in size as its temperature rises, and vice versa. The amount by which different materials change in size for a given temperature difference varies widely, as does the range of temperatures to which different parts of a building's fabric may be subjected. In all but a few instances, the thermal movements of materials are practically the same in all directions. Coefficients of linear thermal expansion for many types of building material are listed in column 2 of Table 1 (in Part 2 of this digest).

Moisture movements

Materials capable of absorbing or releasing water or water vapour will generally be subject to some increase in size as their moisture content increases but not all types of moisture movement are fully reversible, and they are divided into two categories:

Permanent (*irreversible*) changes in size occurring during the early life of some manufactured materials: for example, cement-based products shrink* and fired clay products expand as their moisture contents tend to equilibrium;

Reversible changes in size of both manufactured and natural materials due to changes of moisture content in service.

*Cement-based products will also be subject to a small, continuous shrinkage due to carbonation; however, provided adequate account is taken of moisture movements, it will rarely be necessary to allow for carbonation in addition and no separate data on carbonation shrinkage are given in this digest.

Manufactured materials that are liable to irreversible shrinkage or expansion may also experience subsequent reversible movements if they are subject to changes in moisture content in use. Conversely, some part of the reversible movement of natural materials may in effect be permanent when associated with conditioning prior to installation, as opposed to variations in conditions while in use. The moisture movement of a material will not necessarily be the same in all directions, especially where there is marked orientation in its structure, eg timber. Columns 3 and 4 of Table 1 list the likely extent of moisture movements as a percentage of size, irreversible movements being based on the period from manufacture to maturity and reversible movements on the likely extremes of moisture content in service.

Causes of deformation

An unrestrained homogeneous material subject to a uniform change in its temperature or moisture content will change only in size. All dimensions will be affected, although not necessarily equally when a measure or orientation has been induced in the material by its processing. However, only a proportion of practical situations in building construction will correspond to this simple case. In many instances of thermal movement, and also in most cases of moisture movement, there will be deformation in shape as a consequence of change in size. The deformation may take forms such as bowing, twisting, curling etc, all resulting from the movement having some kind of differential action. Similar types of deformation can result from different causes:

(a) A homogeneous material can be subject to different environments on opposite faces, producing a gradient of temperature or moisture content across its thickness (Fig 1a). In general, the more the environments differ, the greater the relative movement between the faces.

(b) A material subject to a uniform change in environment may be restrained from expanding or contracting uniformly by being attached to a material with a different response to the environment. This can occur when two materials with different coefficients of expansion or moisture movement are fixed or bonded together, (Fig 1b) or when a homogeneous material is fixed eccentrically to a less responsive background by means of rigid or non-accommodating fixings (Fig 1c).

(c) Non-homogeneous materials such as timber, subject to a uniform change in environment, may deform as a consequence of internal variations in their properties, eg bowing and cupping of timber sections on drying. (Fig 1d.)

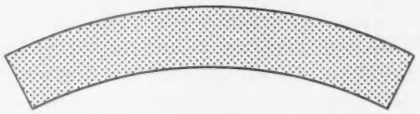
In many cases more than one of these factors may contribute to the total deformation experienced by a material, eg a non-homogeneous or eccentrically restrained material might also be subject to differential environments. In a few cases, one type of action may compensate for another, although it will rarely be possible to design for this to occur. While changes in size can be calculated simply by relating the appropriate coefficient to the change in conditions, the estimation of changes in shape is more complex and requires consideration of the elastic properties of the materials involved. Where theoretical analysis is practicable, it is based on the principles of structural mechanics, which are also needed to assess induced stresses. The extra properties involved are the modulus of elasticity (Young's modulus) and, where applicable, the extent of creep under prolonged stress. Data on Young's modulus are given in Column 5 of Table 1.

In some cases full analysis may not be justified, and design estimates of deformations may instead have to be based on empirical findings.

Fig 1 Causes of deformation and stress

Effects

Higher temperature or moisture level



Lower temperature or moisture level

Deformation, but no stress if gradient across thickness is uniform

(a) Homogeneous material subject to different environments on opposite faces

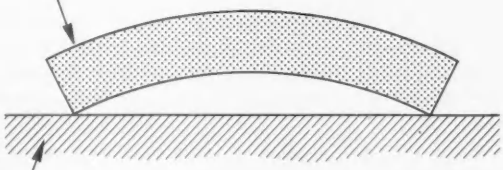
Material with higher coefficient of expansion

Material with lower coefficient of expansion

Deformation plus stress in both materials

(b) Two joined or bonded materials subject to a uniform change of environment

Material with larger response to environmental changes



Material with smaller response to environmental changes

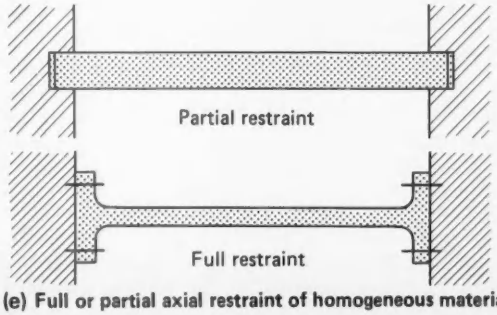
Deformation plus stress in both materials, and in fixings (deformation may be negligible in 'base' material)

(c) Homogeneous material fixed eccentrically to less responsive background

Different strata or areas of material with different responses to environmental changes

Deformation, usually accompanied by some stress due to irregular distribution of response

(d) Non-homogeneous material subject to a uniform change of environment



Primarily stress, possibly consequential cracking; very small lateral deformation (determined by Poisson's ratio for the material)

(e) Full or partial axial restraint of homogeneous material subject to a uniform change of environment

Causes of stress

Stress will be induced whenever a material is restrained from taking up a potential change in size or shape. In many cases the restraint will be provided external to the material by fixings, supports or adjacent materials. However, in composite, laminated or non-uniform materials where differential actions are significant, restraint may arise internally. In some cases both types of restraint may be present and in most cases stresses will be accompanied by deformation. A number of discrete cases can be considered:

(a) A homogeneous material may be axially restrained from taking up a change in size (Fig 1e). Other factors being constant, the greater the cross-sectional area of the material and the higher its modulus of elasticity, the greater the restraining force will need to be. A small lateral deformation, characterised by Poisson's ratio and normally associated with a change in length under load, will occur as a consequence of the restrained change in volume, but is generally insignificant compared to the deformations previously described.

(b) The stresses involved in joined, bonded or eccentrically restrained materials will be only partially relieved by deformation, usually taking the form of curvature in one or two planes (Figs 1b and 1c). The magnitude of the residual stress will depend on the change of size imposed on the material, compared to the change of size when it is unrestrained. The residual stress will therefore vary across the thickness of the material, the variation being proportional to the deformation.

(c) If materials that are liable to deform are restrained from adopting their deformed shapes (eg, by a lateral force) then stress will be induced. The type of stress will depend on the potential deformed shape, so that, for example, materials that would have been subject to curvature will experience bending stresses and shear stresses. The magnitude of the stresses will be proportional to the difference in strain between the deformed and undeformed shapes. Such stresses will occur both where the unrestrained deformation would have involved little or no stress (eg, Figs 1a and 1d) and where other internal or external restraints would have produced a deformed shape plus some stress (eg, Figs 1b and 1c). In the latter case the stresses are superimposed.

As with deformations, the evaluation of stresses requires data on the modulus of elasticity, given in column 5 of Table 1. To ascertain whether a given level of stress is acceptable, it will also be necessary to know the yield stresses or permissible stresses of the material in the modes of stress to which it is subject: compression, tension, bending, shear, etc. This information is usually specific to a particular grade or variety of material, and is not included in this digest. As the strength of many building materials, such as masonry and concrete, is far less in tension than in compression, quite low stresses may give rise to cracking where there is restraint to contraction. The acceptability of this will vary in different situations, according to the criteria governing appearance, durability and other functions.

Characteristics that may need to be considered

Movements

In nearly all cases the *overall extent* of a change in size or shape will be relevant, assessed by reference to the extreme conditions to which the material will be subject. In some cases it will also be necessary to subdivide the overall change into its *positive and negative*

constituents, related to conditions at the time of installation. This is likely to be significant for joints whenever the width of a jointing product is determined at the time of installation, as with sealants (as noted above, this needs to be evaluated together with the effects of inaccuracies). It may prove necessary to consider a range of possible installation conditions and corresponding positive and negative changes.

In a number of cases the *frequency of cycles of change* of size or shape will be significant. This characteristic may not have any direct consequences for the material in question but will very probably affect the fixings or joints that have to accommodate its movement. For thermal movements, both daily and annual cycles may be involved although, in certain cases such as materials affected by heat generated within a building, other cycles may apply. For moisture movements, which show a relatively slow response to environmental changes, only annual cycles are likely to be generally relevant. The extent of the movements associated with subsidiary cycles may need to be estimated. It will normally be possible to judge what proportion of the overall change will occur from the material's situation. If critical, a more precise estimate using dynamic analysis of the relevant influences may be needed.

In some cases the *rate of change* of size or shape may need to be estimated. This again is most likely to be relevant to joints, although certain materials are themselves liable to damage if subject to 'thermal shock'. Some jointing products, especially sealants, can accommodate appreciably less movement if it occurs suddenly rather than gradually. In practice, this characteristic is relevant only to thermal movements. High rates of change can occur in externally exposed materials when subject to intense solar radiation, or when cooled by rain. Sharp rises in temperature are also a characteristic of heating services and any materials in intimate contact with them. To estimate rates of change precisely requires dynamic analysis, but this is likely to be too complex for all but critical cases. It will usually be necessary to know only the class in which the rate falls, eg distinguishing changes taking minutes from those taking hours. This can normally be judged from knowledge of the thermal inertia, surface characteristics and the agents inducing heating or cooling.

Stresses

In nearly all cases the *positive and negative constituents* of the overall range of stresses experienced will need to be known, since these will determine the extreme magnitudes of oppositely acting stresses (eg compression at one extreme, tension at the other). It will generally be necessary to relate these to a range of possible installation conditions so that, for example, stresses due to restrained thermal expansion are assessed in relation to the coldest likely conditions at installation, and vice versa.

The *number of cycles of variation* of stress and their *frequency* may be significant for materials that are liable to fatigue when subject to fluctuating or, especially, reversing stresses. Stresses due to high rates of change of local temperature may also be relevant for materials that tend to degrade or fail under shock effects.

In some cases the *duration* of a particular level of stress will have to be determined. This, together with the stress level, will determine the extent of creep, and any consequent relief of stress, in relevant materials. The duration of stress may also influence the liability of some materials to fatigue. It will need to be assessed in relation to the frequency of cycles of change.

Documents referred to in the text

Digest 199 Getting good fit

Digest 223 Wall cladding: designing to minimise defects due to inaccuracies and movements

Graphical aids for tolerances and fits; HMSO, London; £15·50

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